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EFFECT OF TEMPERATURE AND PRESSURE ON CAVITATION DAMAGE TO A COBALT BASE ALLOY IN SODIUM

by Stanley G. Young and James R. Johnston

Lewis Research Center
Cleveland, Ohio

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ABSTRACT

A vibratory apparatus was used to subject the cobalt-base alloy, L-605, to cavitation damage in sodium at 400^{o}, 800^{o}, and 1200^{o} F (204^{o}, 427^{o}, and 649^{o} C). Cover gas pressures were varied from 1 to 4 atmospheres (10 to 40 N/cm^{2}) at each temperature. Increasing pressure increased the cavitation damage at each test temperature. Damage was greatest at the 800^{o} F (427^{o} C) test temperature for all pressures. A volume-loss-rate contour diagram was constructed to show cavitation damage in terms of the combined temperature and pressure of the sodium.

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SUMMARY

An investigation of the effect of environment on the resistance to cavitation damage of materials under consideration for components of liquid-metal power conversion systems is described. A vibratory apparatus subjected L-605, a cobalt-base alloy, to accelerated cavitation damage in sodium at 400°, 800°, and 1200° F (204°, 427°, and 649° C). Argon gas was used to maintain pressures up to 4 atmospheres (40 N/cm^2) during test. Volume-loss and volume-loss-rate measurements were used to compare the effects of pressure and temperature on cavitation damage.

Increasing pressure significantly increased cavitation damage at the temperatures investigated. Pressure had the maximum effect on damage at 800° F (427° C). Increased pressure had the smallest effect on damage at 400° F (204° C). The average volume-loss rate increased significantly with pressure. When the volume-loss-rate data were normalized to consider only the heavily damaged area of the specimens, the average volume-loss rate increased as a power function of pressure (above approximately 2 atmospheres (20 N/cm^2)) at each temperature.

INTRODUCTION

Proposed space power systems must function on the order of 10 000 hours or longer. Components of such systems have experienced cavitation damage from the circulating liquid alkali metals when tested for several hundred hours in liquid-metal loops (refs. 1 to 3). To determine the resistance of candidate materials to cavitation damage by liquid metals, studies have been made in several laboratories (refs. 4 to 8) using accelerated cavitation damage tests. Extensive work has also been done to investigate the mechanism of cavitation itself and how the cavitation process causes material damage. Some of these investigations are reported in references 9 to 12.

Most investigations of accelerated cavitation damage have been performed at ambient pressures approximately equal to atmospheric pressure. In power conversion systems, however, fluid pressures can vary, depending on the operating conditions, from near the fluid vapor pressure at the pump inlet to hundreds of pounds per square inch at the pump outlet. At the same time substantial differences in temperature exist throughout such systems. Therefore, it is important to establish the combined effects of pressure and temperature on cavitation damage to materials in order to achieve a better understanding of the cavitation phenomenon in space power systems as well as other engineering applications. The effect of pressure on accelerated cavitation damage in water at several constant temperatures was investigated previously (refs. 13 and 14). It was shown that increasing pressure up to approximately 2 atmospheres (20 N/cm^2) increased cavitation damage, but that higher pressures up to 4 atmospheres (40 N/cm^2) suppressed damage.

More recently, the effect of pressures up to 2.7 atmospheres (27 N/cm^2) on cavitation damage in liquid potassium was determined at several temperatures (ref. 8). Variations in the amount of cavitation damage with pressure in potassium at several constant temperatures were found to be similar to those observed for water.

In a recent report (ref. 5) we demonstrated that a direct relation exists between the amount of cavitation damage and the pressure applied to the sodium. These tests were conducted at pressures from 1 to 4 atmospheres (10 to 40 N/cm^2) while a constant fluid temperature of 800° F was maintained. The amount of damage sustained by several different materials increased significantly with increasing pressure. In order to determine the interrelation between pressure and temperature, this investigation was continued.

This paper describes the combined effects of temperature and pressure on cavitation damage to a cobalt-base alloy, L-605.

In conducting this investigation, L-605 was tested in sodium at 400°, 800°, and 1200° F (204°, 427°, and 649° C) using a magnetostrictive vibratory apparatus. Argon gas was used over the liquid sodium to maintain pressures ranging from 1 to 4 atmospheres (10 to 40 N/cm^2). Cavitation damage was determined on the basis of volume-loss measurements. Metallographic studies were made on sectioned specimens after testing.

MATERIALS, APPARATUS, AND PROCEDURE

Materials

The material investigated was the cobalt-base alloy, L-605 (HS-25). This material was chosen because L-605 showed moderate resistance to damage in sodium at atmospheric pressure (ref. 4). The nominal chemical composition of L-605 in weight percent (ref. 15) is as follows:

Cobalt	Balance
Chromium	20
Tungsten	15
Nickel	10
Iron	3 (max)
Carbon	0.1
Manganese	1.5
Silicon	1.0 (max)
Phosphorous	0.04 (max)
Sulfur	0.03 (max)

The as-received material had been solution heat treated at 2250° F (1232° C) and water quenched. The mechanical properties of this alloy are given in table I.

TABLE I. - MECHANICAL PROPERTIES OF L-605

AT TEST TEMPERATURES[a]

Test temperature		Ultimate tensile strength		Yield strength		Elongation, percent
°F	°C	psi	MN/m^2	psi	MN/m^2	
400	204	138 000	950	48 000	330	74
800	427	119 000	820	36 000	250	76
1200	649	99 000	680	34 000	230	48

[a]Ref. 15.

Reactor grade sodium with an analysis of less than 10 ppm oxygen was used as the test fluid. Purity of the sodium was maintained by the addition of a titanium-sponge hot trap to the liquid-metal bath and periodically heating to 1200° F (649° C) for 3 to 4 hours.

Accelerated Cavitation Damage Test Facility

The apparatus used is shown schematically in figure 1. A complete description of the facility and test procedure is given in reference 4. Figure 1 illustrates the vacuum dry-box arrangement, magnetostrictive transducer assembly, and separately sealed liquid-metal test chamber with associated argon line, vapor trap, and pressure gage. The dry box and test chamber were evacuated to a pressure of approximately 10^{-3} torr and backfilled with high purity argon prior to testing.

The specimen was attached to the end of a resonant system consisting of a transducer,

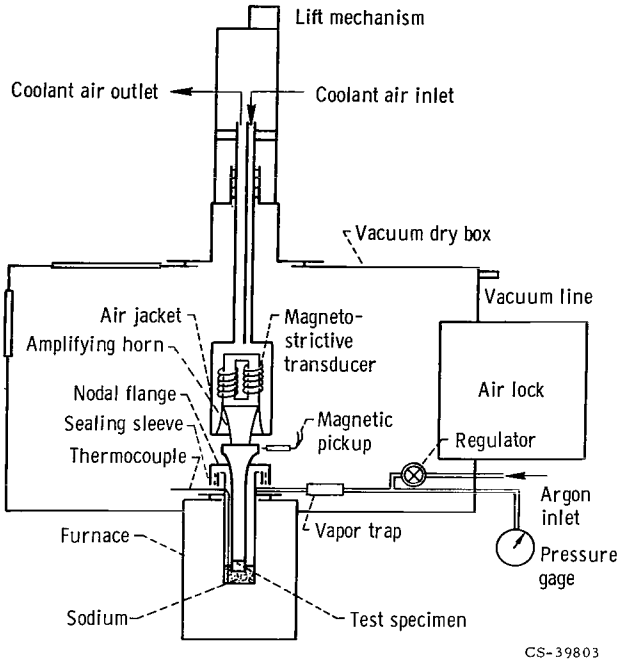


Figure 1. - Schematic diagram of cavitation apparatus.

an exponential horn, and an extension-rod specimen holder. The amplitude and frequency of vibration were detected by a magnetic pickup, and read on an oscilloscope. An automatic feedback system maintained constant amplitude irrespective of variations in resonant frequency induced by temperature changes.

After the liquid bath was brought to temperature, the transducer assembly was lowered into position. A sleeve attached to a nodal flange on the amplifying horn sealed the liquid-metal test chamber from the dry box, and the test chamber pressure was regulated through a separate argon line. Pressures were measured with a precision gage having an accuracy of 0.25 percent. Observed pressure variations were less than 0.25 psi ($1.7\ kN/m^2$).

Test Conditions

The test conditions are listed in table II. The temperature variation within the sodium test bath was no more than $\pm 10^{\circ}$ F ($\pm 6^{\circ}$ C) at any test temperature. The temperature was controlled from a thermocouple directly immersed in the bath. The frequency of vibration of the test specimens was nominally 25 000 hertz, and the peak-to-peak displacement amplitude was 0.00175 ± 0.00005 inch (4.45×10^{-2} mm). The specimen surface was immersed to a depth of approximately 0.13 inch (3.3 mm).

TABLE II. - TEST CONDITIONS

[Material, L-605; fluid, sodium (99.95 percent purity); frequency, 25 000±500 Hz; amplitude, 0.00175±0.00005 in. (4.45×10^{-2} mm).]

Temperature		Pressure[a]		Maximum test time, min
°F	°C	atm	N/cm^2	
400	204	1	10	600
		2	20	↓
		3	30	
		4	40	
800	427	1	10	[b]360
		2	20	600
		3	30	600
		4	40	[b]495
1200	649	1	10	[b]360
		2	20	600
		3	30	600
		4	40	600

[a]Nominal pressure, ±0.02 atm (±0.2 N/cm^2).

[b]Specimen failed at thread.

Test Procedure

The type of specimen used is shown in figure 2. The test surface of each specimen was metallographically polished before test to allow meaningful examination of the specimen surface at high magnification during the early stages of damage. Prior to the test, the specimens were weighed and photographed. After each time increment of operation, the specimens were removed from the apparatus, cleaned, weighed, and rephotographed. Weight-loss measurements were divided by density to obtain volume loss (density of L-605 = 9.13 g/cm^3).

Test duration was dependent on the volume-loss rate at each condition. In most cases, the testing of a specimen was continued for about 600 minutes, a sufficient time to achieve a relatively constant volume-loss rate.

After testing, some specimens were sectioned axially and examined metallographically to determine the depth of cavitation attack and to study any reaction zones that might exist below the surface of the specimen.

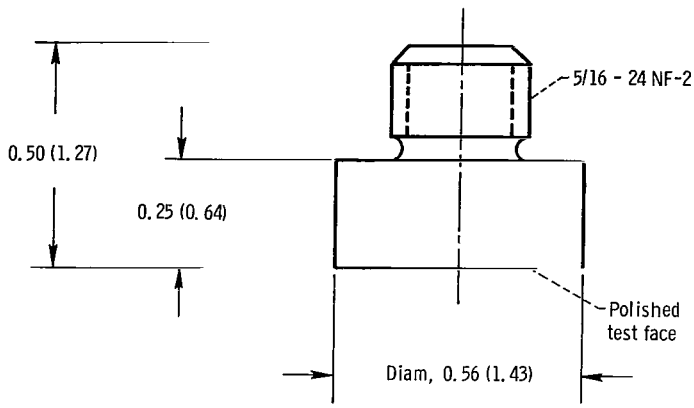
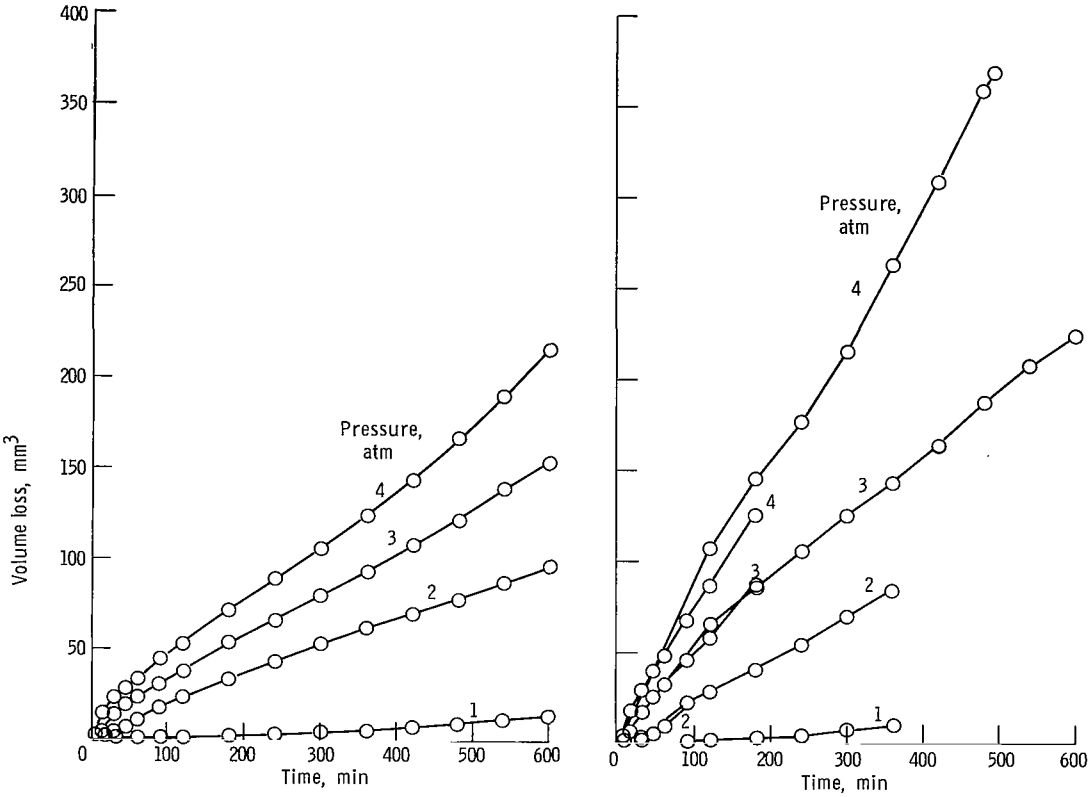


Figure 2. - Cavitation test specimen. (Dimensions in inches (cm).)

RESULTS AND DISCUSSION

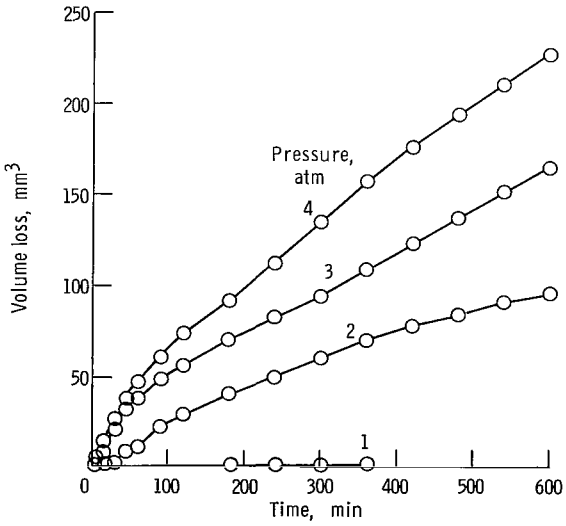
Volume Loss and Volume-Loss Rate

The cavitation damage to L-605 at 1, 2, 3, and 4 atmospheres (10, 20, 30, and 40 N/cm^2) is shown in terms of volume loss at 400°, 800°, and 1200° F (204°, 427°, and 649° C) in figure 3. All these data are summarized in table III. Volume-loss rates are plotted in figure 4. Volume-loss-rate curves were obtained by dividing the volume loss between successive weighings by the increment of test time between them. These values were then plotted midway between the weighing times. From figures 3 and 4 it is evident that at the temperatures of this investigation cavitation at higher pressures results in (1) higher cumulative volume loss, (2) a higher volume-loss-rate peak, and (3) a higher level of average volume-loss rate. The average volume-loss rate was used as an objective measurement of what has in the past been called steady-state volume-loss rate (refs. 4, 5, and 7) and is defined in this investigation as the average volume-loss rate observed between 120 minutes and the termination of the test. For the 1-atmosphere (10 N/cm^2) tests a volume-loss-rate peak was not observed. Therefore, the maximum volume-loss rate was used rather than the average value. When two specimens were run at the same conditions, the one running the longest time was used for these measurements. After 120 minutes the volume-loss rate, for all pressure levels except for the 1-atmosphere (10 N/cm^2) tests, had passed through a peak, and the volume loss rate did not change significantly over an extended period of time. Therefore, the average does, in fact, represent a relatively constant volume-loss-rate value. The calculated average volume-loss-rate values are summarized in table IV. These values are nearly identical for the same pressures at 400° and 1200° F (204° and 649° C) and range from <0.03 to over 0.3 cubic millimeter per minute. At 800° F (427° C) the values range from 0.05



(a) Temperature, 400° F (204° C).

(b) Temperature, 800° F (427° C).



(c) Temperature, 1200° F (649° C).

Figure 3. - Cumulative cavitation damage of L-605 tested in sodium at various temperatures and pressures (1 atm = 10 N/cm^2).

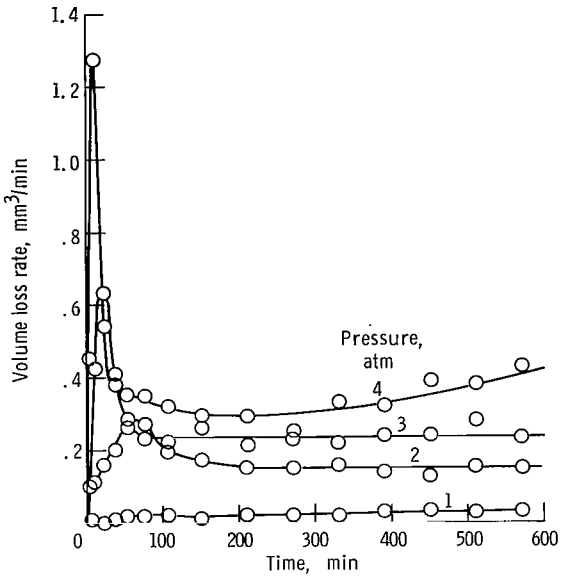
TABLE III. - SUMMARY OF CAVITATION TEST DATA FOR L-605

Temperature		Cover-gas pressure		Time, min													
				5	15	30	45	60	90	120	180	240	300	360	420	480	540	600
°F	°C	atm	N/cm^2	Volume loss, mm^3														
400	204	1	10	0	0	0	0.2	0.6	1.2	1.8	2.5	3.8	4.9	6.2	7.9	9.7	11.5	13.5
		2	20	0	1.2	3.6	6.6	10.5	18.5	24.3	34.4	43.4	52.6	61.9	70.1	78.0	87.2	96.0
		3	30	.5	4.7	14.1	20.2	24.5	31.3	38.0	53.9	66.5	80.3	93.5	107.8	122.4	139.4	153.4
		4	40	2.3	15.0	23.1	28.7	34.0	44.6	54.2	71.6	89.3	104.6	124.5	143.8	166.9	189.7	215.8
800	427	1	10	0	0	0	0	0.1	0.2	0.7	2.3	4.1	7.0	9.4	-----	-----	-----	-----
		[a]2	20	0	.2	2.0	5.3	9.3	19.8	-----	-----	-----	-----	-----	-----	-----	-----	-----
		[b]2	20	---	----	2.8	----	----	21.6	28.4	40.2	53.6	69.4	83.2	-----	-----	-----	-----
		[a]3	30	.5	5.7	16.4	25.2	32.0	44.5	57.7	86.3	-----	-----	-----	-----	-----	-----	-----
		[b]3	30	.2	----	----	----	----	----	65.3	85.0	104.5	125.4	143.2	163.7	186.9	207.0	223.8
		[a]4	40	3.8	17.2	28.9	38.7	47.5	67.3	85.6	125.5	-----	-----	-----	-----	-----	-----	-----
		[b]4	40	2.0	----	----	----	----	----	107.2	144.5	177.5	214.5	262.7	308.5	358.7	(c)	-----
1200	649	1	10	0	0	0	0	0	0	0	0	0.1	0.2	0.5	-----	-----	-----	-----
		2	20	0	.2	2.0	7.9	11.3	21.7	28.6	39.7	49.4	60.3	69.6	77.8	84.4	90.8	94.5
		3	30	.3	7.6	21.1	30.9	37.8	48.3	56.4	70.4	82.2	94.0	109.2	123.3	137.3	151.3	165.1
		4	40	4.0	13.7	26.1	37.8	46.6	60.3	73.7	92.2	112.3	134.7	157.1	176.3	194.4	209.9	226.7

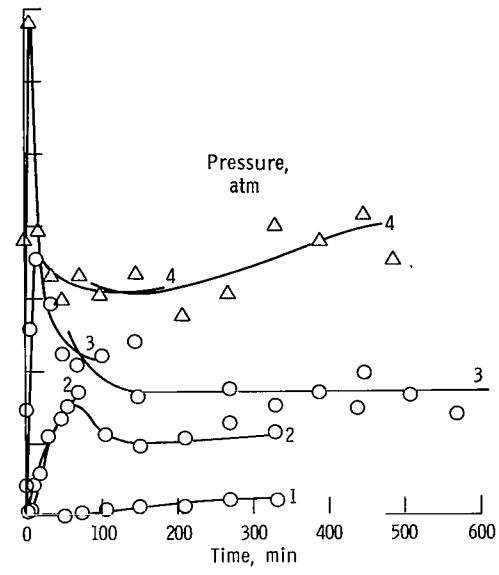
[a]First specimen.

[b]Second specimen.

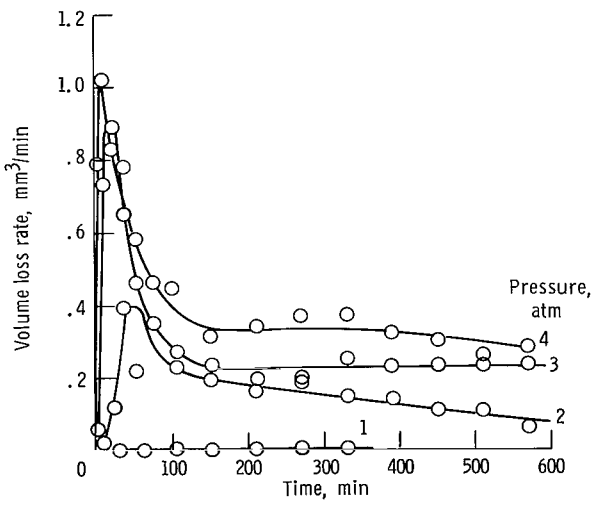
[c]Test terminated at 495 min, volume loss 369.2 mm^3.



(a) Temperature, 400° F (204° C).



(b) Temperature, 800° F (427° C).



(c) Temperature, 1200° F (649° C).

Figure 4. - Rate of cavitation damage of L-605 tested in sodium at various temperatures and pressures (1 atm = 10 N/cm^2).

TABLE IV. - DETERMINATION OF NORMALIZED AVERAGE VOLUME LOSS RATE FOR L-605

Temperature		Pressure		Average volume-loss rate after 120 min, mm^3/min	Heavy damage area,[a] mm^2	Normalizing factor[b]	Normalized average volume-loss rate,[c] mm^3/min
^oF	^oC	atm	N/cm^2				
400	204	1	10	[d]0.03	136	1.18	0.04
		2	20	.15	130	1.23	.18
		3	30	.24	117	1.37	.33
		4	40	.34	104	1.54	.52
800	427	1	10	[d]0.05	137	1.17	0.06
		2	20	.23	132	1.21	.28
		3	30	.40	116	1.38	.55
		4	40	.68	97	1.66	1.13
1200	649	1	10	[d]0.01	135	1.18	0.01
		2	20	.14	102	1.57	.22
		3	30	.23	94	1.71	.39
		4	40	.32	79	2.03	.65

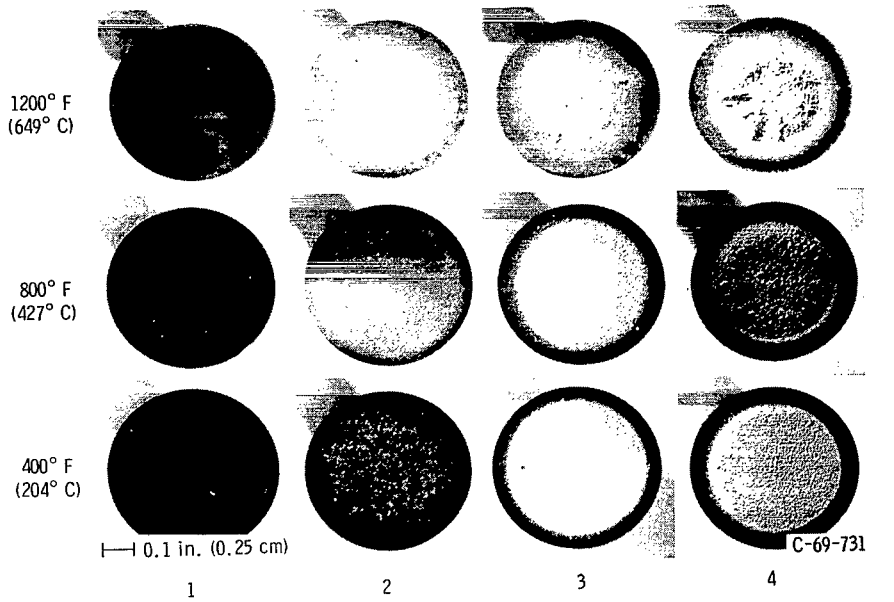
[a](Average diameter of damaged area)$^2 \times \pi/4$.
[b]Ratio of total specimen area (160 mm^2) to heavily damaged area.
[c]Average volume-loss rate after 120 min × Normalizing factor.
[d]Highest observed rate.

cubic millimeter per minute at 1 atmosphere (10 N/cm^2) to about 0.7 cubic millimeter per minute at 4 atmospheres (40 N/cm^2).

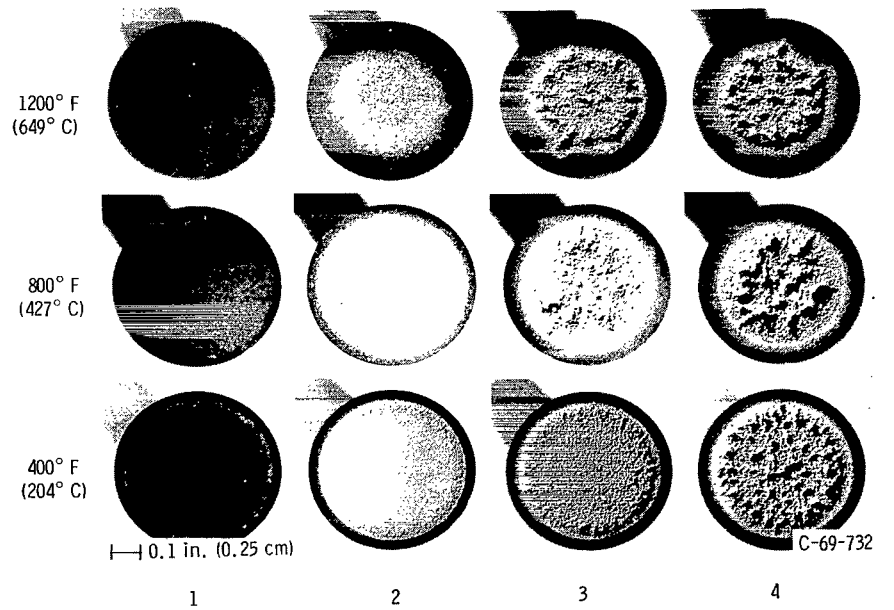
Effects of Temperature and Pressure on Cavitation Damage

Photographs of the damaged surfaces of representative specimens tested for various time increments are shown in figure 5. The undamaged rim area generally increased with both higher test temperatures and higher pressures at each increment of test time. Therefore, the volume-loss-rate data were normalized by multiplying the volume-loss rate by the ratio of the total specimen area to the heavily damaged area. In this manner, the intensive effects of temperature and pressure on volume-loss rate were determined independently of the changes in damaged area. The normalized cavitation damage data also are listed in table IV and plotted in figures 6 and 7.

Within the range of conditions considered in this investigation, it can be seen from

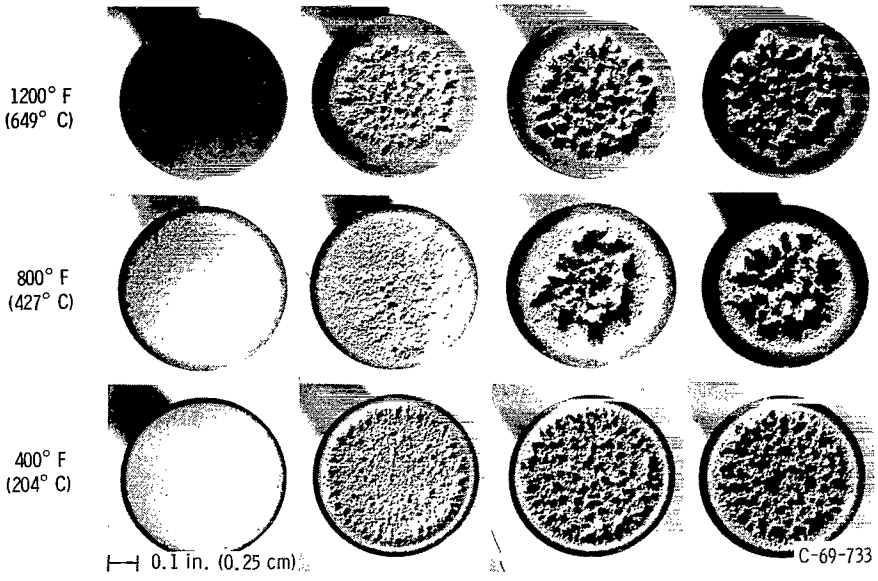


(a) 5 Minutes.

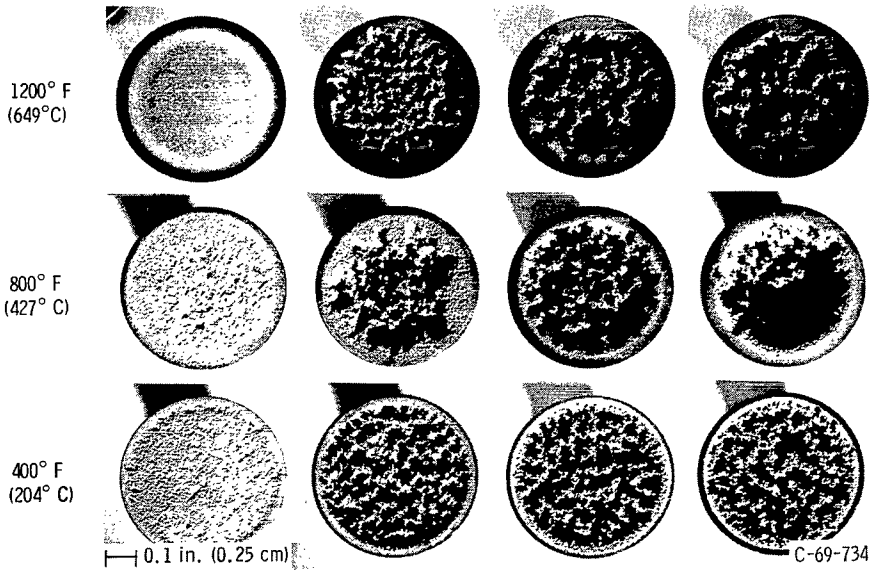


(b) 15 Minutes.

Figure 5. - Damaged surfaces of L-605 specimens after exposure to cavitation in sodium at various temperatures and pressures (1 atm = 10 N /cm^2).



(c) 60 Minutes.



(d) 360 Minutes.

Figure 5. - Concluded.

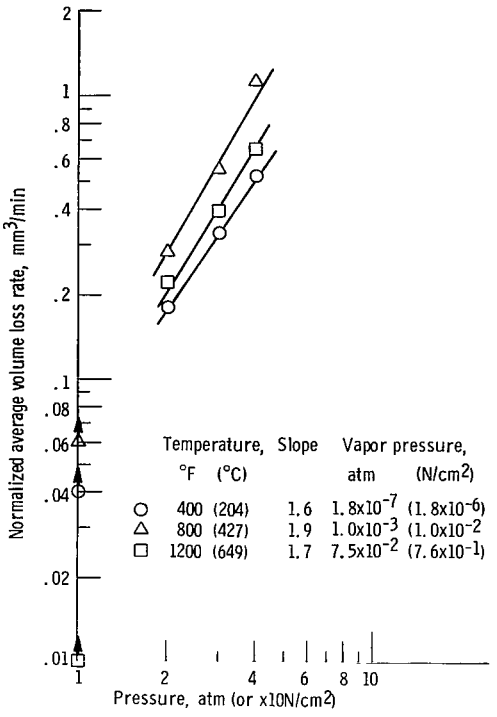


Figure 6. - Relation between normalized cavitation damage rate and ambient pressure for L-605 tested in sodium at various temperatures.

figure 6 that the average volume-loss rate apparently increased as a power of pressure above pressures of 2 atmospheres (20 N/cm^2). Exponents of 1.6, 1.9, and 1.7 were measured for the lines fitted to the 400^o, 800^o, and 1200^o F (204^o, 427^o, and 649^o C) data between 2 and 4 atmospheres (20 and 40 N/cm^2). It should be noted, however, that in figure 6 the data points measured at 1 atmosphere (10 N/cm^2) all fall below extensions of the lines established by the three higher pressure points. Two possibilities could account for this. First, cavitation damage must be zero at pressures approximately equal to the vapor pressure of the fluid. The values of vapor pressure are given in figure 6. On the logarithmic plot of figure 6, if the linear relation held at the lower pressures (in the vicinity of 1 atm (10 N/cm^2) and below), zero damage would be approached only at pressures very much lower than the vapor pressures. Therefore, the curves must fall away from the linear relation toward the pressure axis at low pressure, and this fall off apparently begins between 1 and 2 atmospheres (10 and 20 N/cm^2). Second, the volume-loss rates were still increasing before termination of all the 1-atmosphere (10-N/cm^2) tests. As a consequence, the average volume-loss-rate values plotted may be lower than would have been observed if very long test times had been used to establish the exact value of an average (constant) volume-loss rate. At higher pressure the rates were relatively constant after only 120 minutes.

The volume-loss results from the 800° F (427° C) tests of this investigation were consistently higher than 800° F (427° C) tests reported in a previous report (ref. 5). However, in the present work, damage patterns were more uniform than in the earlier tests. Also, new feedback equipment maintained a more consistent amplitude than was possible with earlier equipment. The slope of the log damage against log pressure curve reported in the earlier paper was approximately 2.2. A line with a similar slope can be fitted through the 800° F (427° C) data of this report. However, when the 800° F (427° C) data of this report are considered in relation to the 400° and 1200° F (204° and 649° C) data, the results are more consistent if the curves are considered to be linear only between 2 and 4 atmospheres (20 and 40 N/cm^2). Consequently, the slope of the 800° F (427° C) curve between 2 and 4 atmospheres (20 and 40 N/cm^2) is shown as 1.9 rather than the somewhat higher value that would have resulted if the data at 1 atmosphere (10 N/cm^2) had also been considered in fitting this curve.

Figure 7 shows the effect of temperature on cavitation damage at four different pressures. The maximum normalized volume-loss rates were observed at 800° F (427° C) for all test pressures. The true shapes of these curves can only be conjectured, however, because many different curves can be drawn through three points. More experimental data are needed to define completely the shapes of the curves for this figure. The cavitation damage rates at 1 atmosphere (10 N/cm^2) were not in the same order with respect to temperature as the rates measured at higher pressures. Damage was least at 1200° F (649° C) and 1 atmosphere (10 N/cm^2), but for 2, 3, and 4 atmospheres (20, 30, and

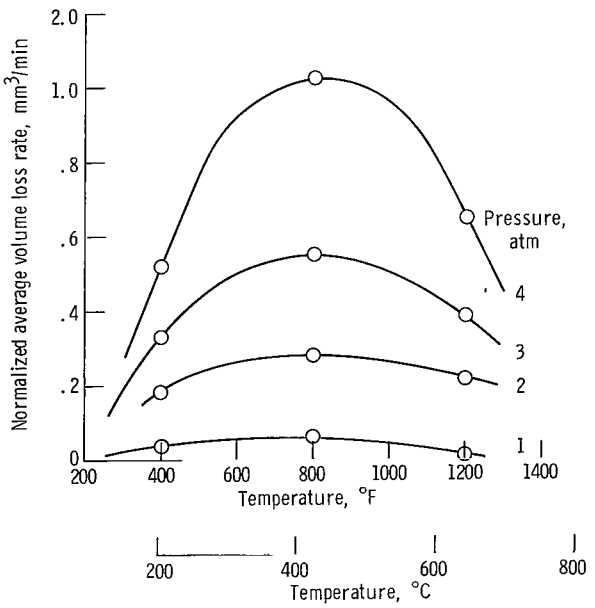


Figure 7. - Relation between normalized cavitation damage rate and temperature for L-605 tested in sodium at various pressures (1 atm = 10 N/cm^2).

40 N/cm^2) it was least at 400^o F (204^o C).

To help visualize the combined effects of the temperature and pressure of the cavitating fluid on cavitation damage, figure 8 was constructed. This figure is an average volume-loss-rate contour diagram with temperature and pressure as the axes. The two theoretically limiting curves for zero cavitation damage rate are the solid-liquid and liquid-vapor curves. It is believed that, as pressure increases, the constant volume-loss-rate contours may close again because of the suppression of cavitation by high pressures. However, because of power limitations of the test facility, pressures above 4 atmospheres (40 N/cm^2) were not investigated.

The quantitative values of damage shown in figure 8 would obviously be different for different types of test facilities and for different test amplitudes and frequencies because damage is dependent on the amount of cavitation generated; however, the general trend of increasing damage with increasing pressure is valid. Further tests at other temperatures and higher pressures are needed to determine the combination of temperature and pressure that would cause maximum cavitation damage with this facility for L-605 as well as for other materials.

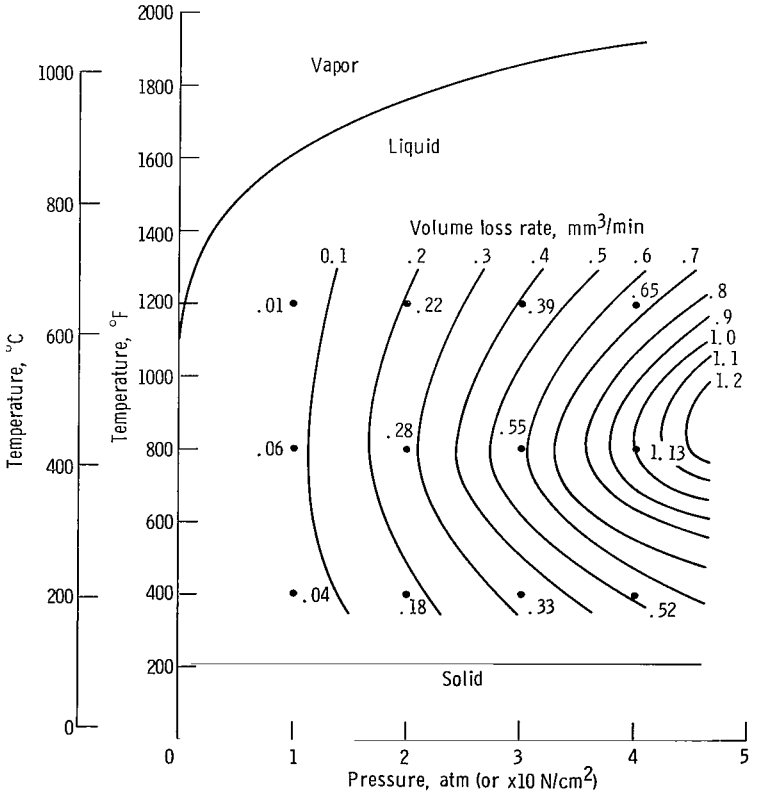
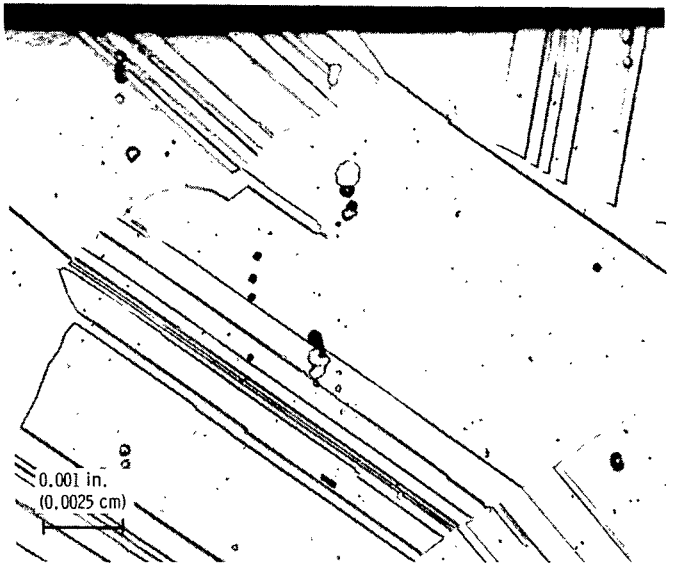


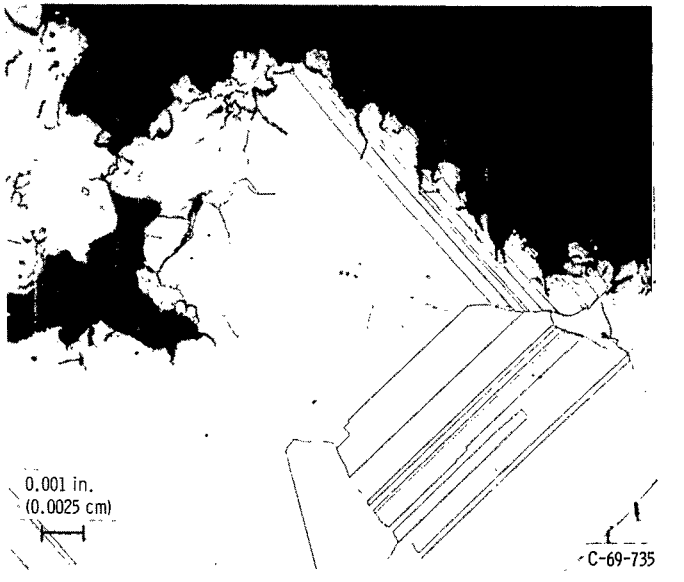
Figure 8. - Effect of temperature and pressure on normalized cavitation damage rate for L-605 tested in sodium.



As-received.

600-Minute exposure at 400° F (204° C).

495-Minute exposure at 800° F (427° C).



600-Minute exposure at 1200° F (649° C).

Figure 9. - Photomicrographs of sectioned specimens of L-605 before and after exposure to cavitation in sodium at 4 atmospheres (40 N/cm^2).

During the cavitation tests, the power required to maintain constant amplitude increased with increasing pressure. An approximate measure of the relative power input to the transducer was the product of the output voltage from the power supply and the plate current of the output tubes. The observed input power required to maintain constant amplitude increased approximately 3 times as the pressure was increased from 1 to 4 atmospheres (10 to 40 N/cm^2). Further work is necessary to clearly establish the relation of increased power requirements with increased pressure to cavitation damage.

Metallography

Photomicrographs were taken of sectioned specimens of L-605 after testing at 4 atmospheres (40 N/cm^2) at each temperature. Results similar to those reported earlier (ref. 5) were obtained (fig. 9). The specimens exhibited gross undercutting and transgranular cracking. Evidence of subsurface deformation existed in the form of slip bands near the surface.

SUMMARY OF RESULTS

A vibratory apparatus was used to investigate the effect of temperature and pressure of cavitating liquid sodium on cavitation damage to the cobalt-base alloy, L-605. This material, which is known to have moderate resistance to cavitation damage, was subjected to cavitation in sodium at 400°, 800°, and 1200° F (204°, 427°, and 649° C) at pressures of 1 to 4 atmospheres (10 to 40 N/cm^2). The following major results were obtained:

1. Increasing pressure significantly increased cavitation damage to L-605 at the test temperatures and times investigated.

2. At each temperature the average volume-loss rate increased with pressure. When the average volume-loss rate was normalized to consider only the heavily damaged area of the specimens, volume-loss rate increased as a power function of pressure (above 2 atm (20 N/cm^2)) with the exponents of 1.6, 1.9, and 1.7 for test temperatures of 400°, 800°, and 1200° F (204°, 427°, and 649° C), respectively.

3. The cavitation damage rates at 1 atmosphere (10 N/cm^2) were not in the same order with respect to temperature as at the higher pressures. Damage was least at 1200° F (649° C) at 1 atmosphere (10 N/cm^2), but for 2, 3, and 4 atmospheres (20, 30, and 40 N/cm^2) damage was least at 400° F (204° C).

4. The effect of temperature and pressure on cavitation damage was expressed as an average volume-loss-rate contour diagram with temperature and pressure as the axes.

This plot suggests that there are definable combinations of temperature and pressure where cavitation damage is maximum.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 4, 1969,
129-03-03-03-22.

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